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FLIGHT EVALUATIONS OF VARIOUS LONGITUDINAL HANDLING QUALITIES IN A VARIABLE-STABILITY JET FIGHTER

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FOREWORD

This report was prepared for the United States Air Force by the Cornell Aeronautical Laboratory, Inc., Buffalo, New York in partial fulfillment of Contract AF 33(038)-20659, Part I Paragraph (a), Expenditure Orders 460-32-13 BR-1, R-461 BR-1, and R-472-501-SR-1Z, and completes the requirements of this contract.

The program was performed by the Flight Research Department of Cornell Aeronautical Laboratory, Inc., under the sponsorship of the Aeronautical Research Laboratory, Wright Air Development Center, Air Research and Development Command, U.S. Air Force as Task 70501 of Project 1364, "Flight Control Technical Requirements". This is part of a basic program to determine the optimum and minimum acceptable longitudinal stability and control characteristics. Mr. P.P. Cerussi, was Task Scientist for the Aeronautical Research Laboratory.

Design and development of the instrumentation and servo system was the responsibility of the Instrumentation Section of the Flight Research Department under Mr. W.J. Hirtreiter. The flight evaluations were performed by Mr. J.C. Seal, Chief Test Pilot.

The work of Mr. F.D. Newell is due particular recognition for his contributions to the analysis of the pilot opinion data and the design of the experiment.

ABSTRACT

An F-94A jet fighter was modified to provide variable longitudinal stability and control characteristics, thus permitting in-flight variations of the longitudinal handling qualities. Evaluations were conducted in flight by one pilot for a variety of short period dynamics, stick force gradients, and stick displacement gradients. The pilot comments are discussed and the objections related to the time history of the airplane response. Qualitative ratings are shown as areas of varying degrees of the pilot's acceptance of these characteristics.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Aldro Lingard
ALDRO I. LINGARD
Colonel, USAF
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Directorate of Research

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LIST OF SYMBOLS

cg	Airplane center of gravity location
C_{m_α}	Pitching moment coefficient per unit angle of attack, per radian
F_s	Pilot-applied stick force, pounds
$F.R.$	Fuel Remaining
n_z	Incremental normal acceleration, g units
RT	Response time, seconds
TPR	Transient peak ratio
u	Incremental forward velocity, feet per second
$\dot{u}$	Time rate of change of forward velocity, feet per second per second
α	Angle of attack, degrees
$\dot{\alpha}$	Time rate of change of angle of attack, degrees per second
δ_e	Elevator angular displacement, degrees
δ_s	Linear displacement of pilot's control stick at grip, inches
ζ	Short period damping ratio
θ	Pitch attitude angle, degrees
$\ddot{\theta}_0$	Initial pitch acceleration, degrees per second per second
ω_n	Short period undamped natural frequency, radians per second
f_n	Short period undamped natural frequency, cycles per second

home? With the answer in view, the designer can arrive at a configuration in which there is the least compromise of performance consistent with good handling qualities.

In order to provide some information about these problems, the Cornell Aeronautical Laboratory, under the sponsorship of the Aeronautical Research Laboratory of Wright Air Development Center, has undertaken a flight research program on the longitudinal handling qualities of bomber and fighter type aircraft. The results of the bomber-type investigation are described in References 1 and 2. This report describes the results of the fighter-type airplane investigation.

The following items were selected as some of the more important parameters which would be varied in these tests.

1. Short period natural frequency, ω_n, and damping ratio, ζ.
2. Stick force per normal acceleration, F_s/n_z.
3. Stick displacement per normal acceleration, δ_s/n_z.

Equipment is provided also to vary the phugoid period and damping, but was not used in this evaluation. The phugoid parameters were varied in the B-26 tests, and the results are described in Reference 2.

EQUIPMENT

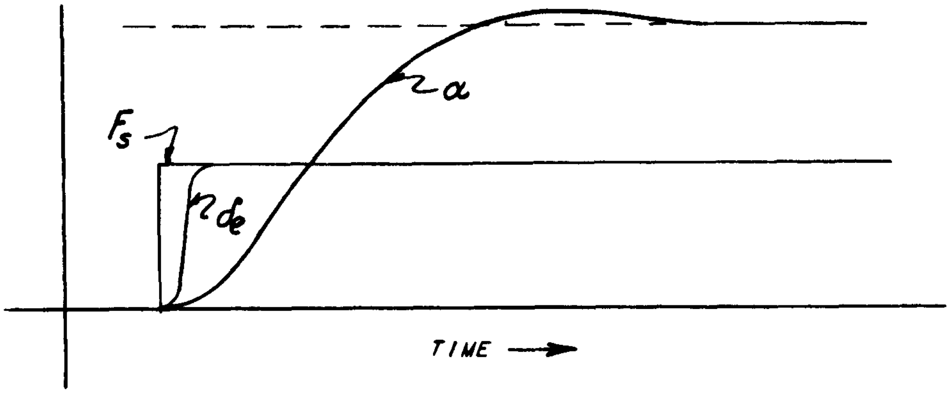
An F-94A jet fighter airplane was supplied by the Air Force. The airplane was modified by Cornell Aeronautical Laboratory into a variable-stability airplane by the design and installation of three position servos and suitable sensing and recording instrumentation. A detailed description of the equipment is contained in Reference 4.

The dynamics of the short period are varied by applying moments to the airplane with the elevator. The elevator is positioned by an irreversible electro-hydraulic servo in response to the pilot's stick force signals and to signals proportional to certain selected airplane responses. The elevator motion proportional to the airplane response applies moments to the airplane which modify the dynamics of the airplane in a manner similar to actually varying the stability derivatives themselves.

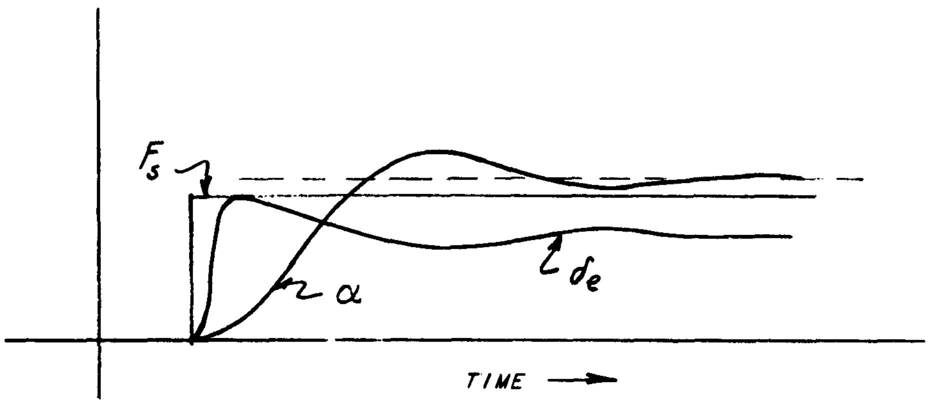
The response parameters angle of attack, α , and time rate of change of angle of attack, $\dot{\alpha}$, were chosen to vary the natural frequency and damping ratio of the short period. As described in Reference 3, the use of these variables permitted a more independent variation of frequency and damping, and had little effect upon the phugoid response.

Angle of attack is measured by a vane mounted on the forward end of a nose boom. Angle of attack rate is obtained by passive network differentiation of the α signal. After passing through gain controls located in the aft cockpit, these signals are mixed with the pilot's stick force signals and fed as inputs to the elevator servo.

An example will serve to show how these inputs modify the response of the airplane to the pilot's input. Consider first the airplane when operating on servo control, but without artificial stabilization signals being supplied to the servos. The pilot applies a step force input and the time history of the response is as shown on the following page.



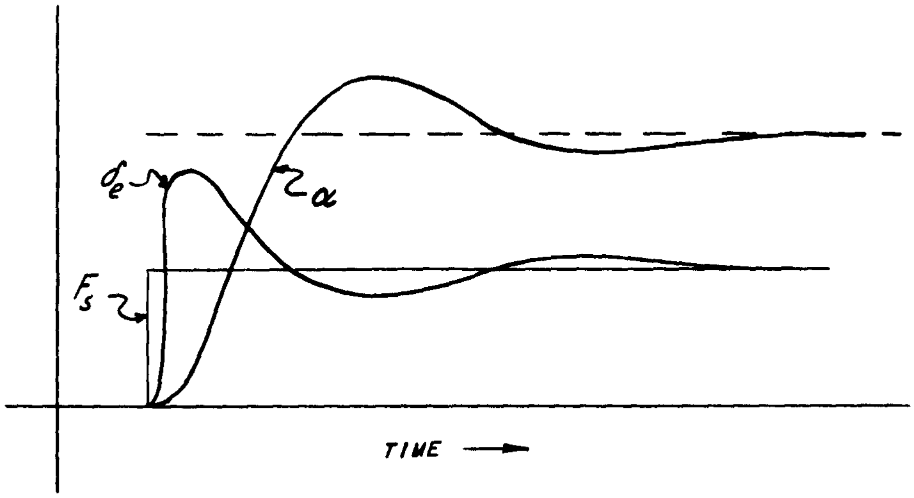
Now assume some positive* α is fed to the elevator servo to stiffen or speed up the short period response. The α signal reduces the initial elevator angle as the airplane responds. The airplane reaches a new, but smaller, steady state α faster than before as shown below. Thus, the response has been speeded up but the statics (F_s/n_z) have changed.



If the force gain to the elevator servo is increased, the result will be a faster, higher natural frequency short period response with the same

* *Using conventional sign notation, the static sensitivity of the airplane, α/δ_e , is negative and thus positive feedback simulates moving the cg forward and is stabilizing.*

steady state stick force per g:



In a similar manner, the $\dot{\alpha}$ signals cause incremental elevator angles which apply moments to the airplane and modify the short period damping.

It can be seen from the above discussion that it would be most undesirable for the pilot to feel in his control stick the elevator motions due to α and $\dot{\alpha}$. For this reason, as well as to provide a readily-variable force feel, a second servo was installed to position the pilot's control stick in response to his force inputs.

Thus two servos are required - one to position the pilot's control stick, the other to position the elevator, with no mechanical connection between stick and elevator when the servo system is engaged. Both servos have a common stick force input and thus simulate a mechanically connected control system.

An outstanding feature of this servo system is the almost-negligible breakout force. The use of a force signal obtained from strain gages as the input to the elevator servo eliminated the resolution problem usually encountered in measuring stick position for the input. The stiction in the spool of the electro-hydraulic transfer valve was reduced to a very small value by exciting the spool continuously with a 400 cps "dither voltage". The result was a breakout force of four ounces at a stick force per g of 8.5 lb/g.

A block diagram of the servo system is shown in Figure 4. The gain controls are located on a control panel in the aft cockpit and are easily varied in flight. The short period natural frequency and damping ratio are varied by adjusting the gains of the α and $\dot{\alpha}$ feedback signals. The F_s/n_z is varied by adjusting the force gain to the elevator servo, and the stick displacement per stick force (δ_s/F_s) is varied by adjusting the force gain to the stick servo.

Equipment is also provided to modify the dynamics of the phugoid, or long period mode of oscillation. Signals proportional to changes in velocity, u , and time rate of change of velocity, $\dot{u}$, are provided. Moments proportional to these signals may be applied to the airplane to vary the period and damping of the phugoid. The moments required are very small. If the elevator is used to apply these moments, the angles involved are so small that the resolution of the elevator servo becomes critical. To sidestep this difficulty, a small (one-half square foot) canard auxiliary surface was installed near the nose. The surface can be seen in the photograph of Figure 1, and it is driven by an electric positional servo in response to signals proportional to u and $\dot{u}$.

The phugoid evaluations with the F-94 have been deferred to a later date in order to investigate further the short period and force feel characteristics. The results of the B-26 phugoid evaluations are described in Reference 2.

The rear cockpit in the F-94 ordinarily seats the radar operator and his equipment. The CAL F-94 rear cockpit was modified to include a control stick actuating the ailerons and elevator. No rudder controls are provided. This seat is occupied by a qualified pilot who acts as safety pilot and adjusts the gain controls to vary the longitudinal handling qualities. This aft cockpit control stick is always connected to the elevator.

The evaluation pilot is seated in the front cockpit. For takeoff and landing, the control system is normal with both control sticks mechanically connected to the elevator. When test altitude is reached, the safety pilot takes over control of the airplane. The front pilot disengages his stick from the elevator push rod and engages it to the stick servo strut by positioning the stick servo engage lever. The actuator strut of the elevator servo is then connected to the elevator linkage at the rear cockpit control stick by another lever located on the front pilot's control stick. For take-off and landing, this strut is disconnected from the elevator linkage. The front stick installation and servo engage levers are shown in Figure 2.

After both servos are engaged, the gain controls are set and the evaluation may be commenced. When the pilot has completed his evaluation, the safety pilot repositions the gain controls shown in Figure 3 and another short period and force feel configuration is ready for evaluation.

Thus the pilot is able to compare greatly different airplane stability and control characteristics during a single flight. He feels none of the artificial stability inputs in his control stick, and can effectively and efficiently evaluate this variety of airplane characteristics.

EVALUATION PROCEDURE

The program for evaluating various short period dynamics, stick forces per normal acceleration, and stick displacements per normal acceleration was conducted at an altitude of 20,000 feet in maneuvering flight. For each configuration of ζ, ω_n, F_s/n_z, and δ_s/n_z, the pilot executed four maneuvers designed to help him determine his opinion of the handling characteristics. The maneuvers and instructions given to the pilot were:

a. Trim the airplane in level flight at 300 knots IAS and fly level for at least one minute. Note relative ability to trim at the desired airspeed, ability to remain in trim, and any oscillatory motion.

b. Make abrupt control steps to +2g, +3g, and 0 g absolute accelerations. Note airplane response time and any oscillatory motion.

c. Make slow and rapid entries into level turns, holding sight on horizon. Continue turns up to 180°, noting relative ease and accuracy of tracking the horizon with elevator control.

d. Trim at 180 knots IAS. Push over on a specific ground target (approximately 20° dive angle) and stay on target until speed reaches 280 knots IAS. Pull +3 g's in recovery to level flight. Note relative ability to get on target rapidly and accurately, and relative accuracy of maintaining recovery load factor.

The sequence of performing the maneuvers was random in order not to prejudice the pilot's over-all opinion of the configurations by always doing a particular maneuver last. After completing each maneuver, the pilot's comments and observations were recorded on a tape recorder. Upon completion of all the maneuvers, the pilot recorded a summary of his observations and assigned an over-all opinion according to the following rating scale and definitions:

1. Optimum - This configuration is the best all around. It combines best precision of control with most comfortable control.
2. Acceptable Good - Noticeably better than acceptable but still could

be improved. For example, very comfortable to fly but not the best control precision.

3. Acceptable - In this configuration, the airplane's mission could be accomplished reasonably well, but with considerable pilot effort or attention required directly for flying the airplane.
4. Acceptable Poor - Airplane safe to fly, but pilot effort or attention required is such as to reduce seriously the effectiveness of the airplane in accomplishing its mission.
5. Unacceptable - Pilot effort or attention required to the extent that the airplane's ability to accomplish its mission is doubtful. Or, airplane would be unsafe to fly if pilot's attention is required for navigation, radio, combat, etc.

The pilot was permitted to attach a plus or a minus to the ratings given above if he felt a finer breakdown was necessary.

The ratings as given by the pilot are all specifically applied to fighter-type aircraft with the strength limits of present-day fighter airplanes.

As the program progressed, it became evident that the pilot was not using the optimum rating, and at no time in the program did he use it. He felt that this rating should be saved until he was shown something better than all the rest. The program ended with "Acceptable Good, plus" as the top rating given.

The "learning time" of the pilot was an important consideration of the program. By this is meant the time required for the pilot to fly a particular configuration and be able to assign a well founded and repeatable opinion to it. In this program, the pilot himself judged his learning time. The evaluation period per configuration was lengthened and shortened until the pilot determined the minimum length of time in which he could complete the four maneuvers and be reasonably well acclimated to the configuration in question. This time interval varied from 12 to 15 minutes per configuration. With the tip tanks installed on the airplane, the pilot was able to evaluate four configurations per flight.

The pilot was not informed of the characteristics of the configurations or the actual gain settings, and gave his comments and ratings solely on his evaluations and observations. Certain configurations were repeated several times during the program in order to determine the consistency and repeatability of the experiment.

FLIGHT CALIBRATIONS

The purpose of the flight calibrations was to associate an accurate value of ζ , ω_n , F_s/n_z , and δ_s/n_z with each pilot evaluation. This proved to be more difficult than was at first anticipated.

The primary object of this phase was a plot of short period natural frequency and damping ratio as a function of the α and $\dot{\alpha}$ gains to the elevator servo. These gains produce incremental changes in the short period "stiffness" and damping of the basic airplane. Therefore, any variations in the dynamics of the basic airplane would affect this plot. It was these variations that made the calibration difficult.

The dynamics of the short period of the basic airplane varied with fuel consumed and with the amplitude of the response. The variation with fuel consumed was particularly important because of the low static margin common in fighter airplanes. It could be predicted theoretically from the cg variation given in the Weight and Balance Handbook for the F-94. The variation with amplitude of response was unexpected, and had to be determined experimentally. It was attributed to a non-linear variation of C_m with α . In the course of the determination of the amplitude effect, it was found that the cg variation with fuel consumed differed somewhat from that predicted from the Weight and Balance Handbook, and the actual variation of cg with fuel consumed was also determined experimentally.

The calibration maneuvers consisted of recording the airplane response to stick force pulse and step inputs at 300 knots IAS at 20,000 feet. The time history of the normal acceleration response to the pulse input was analyzed by established techniques (Reference 5) based upon the assumption of a second order response, to obtain ω_n , and ζ of the short period. The F_s/n_z and δ_s/n_z were obtained from the time history of the step response.

These calibration maneuvers were performed for a variety of gain settings before the evaluation phase began. A preliminary gridwork of lines of constant ζ and ω_n as functions of the gains δ_e/α and $\delta_e/\dot{\alpha}$ was constructed and used for programming the evaluation phase. This early calibration was not sufficiently accurate for associating pilot opinion data with particular values of ζ and ω_n because of the variation of these parameters with fuel remaining and with amplitude of the response. In view of this difficulty, one pulse and one step response were performed during each evaluation made by the pilot throughout the rest of the program. In addition, numerous basic airplane responses were recorded.

The data determined from any one response was subject to certain errors. A major source of error was due to the presence of extraneous inputs to the airplane following the pilot-applied force pulse or step input. The analysis procedure assumed a free oscillation and any disturbance such as a gust violated this assumption, causing errors in the calculated ζ and ω_n. Additional errors were introduced by inaccuracies in reading zero time from the first peak of the pulse response. Also, repeatability of the equipment was limited by the resolution of the sensing instrumentation and servo actuators, causing a certain amount of scatter in the calculated data. And, not every record was useable because of recording malfunctions, imperfect inputs, etc. For these reasons, the pilot opinion of a configuration could not be associated directly with the ζ and ω_n determined from the pulse response taken during the evaluation.

The validity of the results of this research program depended to a large extent upon the accuracy with which the pilot's opinion could be associated with the value of ζ and ω_n which he was evaluating. Use of the preliminary gridwork which neglected the effects of varying dynamics with fuel remaining and amplitude of response for making this association, or use of the dynamics determined from the pulse taken during the evaluation, did not produce satisfactory results. The importance of this part of the program justified a more thorough analysis to take into account the effects of the variable cg and C_{m_α}.

When the flight evaluations were completed, all the pulse and step response data were collected. Sufficient basic airplane responses were available at the same fuel remaining to determine the variation of natural frequency with amplitude of response. This value was $f_n = 0.1$ cps per g, evaluated about +2.0 g absolute. This was checked at several values of fuel remaining.

Using this value, all measured values of ζ and ω_n were corrected from those of the actual amplitude of response to the values of a 1.0 g incremental response. The damping term, $2\zeta\omega_n$, was experimentally determined to be independent of the amplitude of response, and the measured values of ζ were corrected for amplitude of response by:

$$\zeta_{1.0g} = \omega_{n_{meas.}} / \omega_{n_{1.0g}} \; \zeta_{meas.}$$

It must be remembered that the values of ζ_{meas} and $\omega_{n_{meas}}$ are those associated with the best second-order fit to the actual airplane short period response. After the above corrections are applied, the fit is specified for an incremental 1.0 g response.

The values of ω_n (now specified for 1.0 g incremental response amplitude) for the basic airplane were plotted versus fuel remaining. This variation did not completely agree with the theoretical variation. The differences were attributed to the sequence in which fuel was used from the various tanks. The theoretical variation assumed that fuel was completely exhausted in one tank before use of the next tank was begun. It was felt that since the sequencing of all internal tanks was controlled by floats, there would be some overlap due to fuel sloshing.

The measured variation of the basic airplane ω_n with fuel remaining was used to reduce the calibration data to one reference value of fuel remaining for constructing the gridwork of short period ζ and ω_n versus the artificial stability gain settings, δ_e/α and $\delta_e/\dot{\alpha}$.

When the ω_n and ζ calibration data was assembled and plotted versus δ_e/α and $\delta_e/\dot{\alpha}$, it was difficult to fair by eye accurate lines of constant ζ and ω_n through the corrected experimental data. A theoretical gridwork, shown in Figure 11, had been constructed using the available flight data on the airplane, and ground calibrations and frequency responses of the servo system. A discussion of the method used in constructing this theoretical gridwork is contained in the appendix of Reference 2.

It was observed that the deviations of the experimental grid from the theoretical appeared to be linear functions of ζ and ω_n (See Appendix). A least squares fit was made of the experimental data to the theoretical grid. This method is discussed in the Appendix. The resultant final calibration of ζ and f_n versus δ_e/α and $\delta_e/\dot{\alpha}$ is shown in Figure 12 for a reference fuel remaining of 350 gal and an amplitude of response of +1.0 g incremental normal acceleration.

Figure 12 was used in the following manner. From the settings of δ_e/α and $\delta_e/\dot{\alpha}$, values of f_n and ζ were determined from Figure 12. These values then were corrected for the difference between 350 gal and the actual fuel remaining in the middle of the pilot evaluation. This stiffness correction was based on the basic airplane calibration of f_n versus fuel remaining. These corrected values of f_n and ζ were those associated with the pilot opinion ratings of Figure 5 and are specified as values for a +1.0 g response amplitude.

Corrections to the flight calibration values of F_s/n_z and δ_s/n_z were also made for fuel remaining and the corrected values are specified for a +1.0 g amplitude of response.

DISCUSSION OF RESULTS

The results and conclusions contained herein are those of a program to vary the longitudinal dynamics of the airplane in flight and obtain pilot opinion data of the longitudinal handling qualities of the pilot-airplane combination. The results covered in this report include those of varying the following parameters.

1. Short period natural frequency and damping ratio.
2. Stick force per normal acceleration.
3. Stick displacement per normal acceleration.

The evaluation program was planned to determine the pilot's opinion of the pilot-airplane combination as a function of four variables: ω_n , ζ , F_s/n_z , δ_s/n_z . To evaluate the pilot's opinion for all combinations of these variables was not possible. The evaluation program was concentrated on:

1. Evaluation of short period dynamics at constant (and desirable) values of F_s/n_z and δ_s/n_z .
2. Evaluation of F_s/n_z and δ_s/n_z at constant (and desirable) short period dynamics.
3. Evaluation of F_s/n_z and δ_s/n_z at three other values of ζ and ω_n :
   a. High frequency - low damping ratio
   b. Low frequency - low damping ratio
   c. Moderate frequency - high damping ratio

Parts (1) and (2) are the areas of most general interest and the major effort was concentrated there. Part (3) was an attempt to determine the "interactions" of ω_n and ζ upon the pilot's opinion of various levels of F_s/n_z and δ_s/n_z . In particular, looking at the pilot-airplane combination, part (3) would provide information as to the practicability of improving the over-all response by modifying the loop gains - i.e., F_s/n_z and δ_s/n_z - when the airplane response is poor.

It will be noted that F_s / n_z and ζ are plotted on a logarithmic scale in the figures. It is felt that the pilot is primarily sensitive to percentage changes in F_s / n_z. That is, he can more readily detect the difference in feel between 2 and 4 lb/g than between 16 and 18 lb/g. The logarithmic scale gives equal space to equal percentage changes from a reference value and is used for this reason.

Damping ratio was plotted to a logarithmic scale because the change in the shape of the response was much greater (and hence, much more evident to the pilot) when, for example, ζ is changed from 0.2 to 0.3 than when it is changed from 1.0 to 1.1. The logarithmic scale emphasized this.

EVALUATION OF VARIOUS SHORT PERIOD DYNAMICS AT CONSTANT STICK FORCE AND DISPLACEMENT PER NORMAL ACCELERATION

The pilot opinion data of the pilot-airplane combination is shown in Figure 5 as a function of the natural frequency and damping ratio of the airplane-alone short period response.

During this evaluation, the stick force per g varied from 7.7 to 10 lb/g, with a mean value of 8.6 lb/g. Similarly, the stick displacement per g varied from .18 to .24 inches/g with a mean value of .21 inches/g.

The data shown is for one pilot with an evaluation time of 12 to 15 minutes per point. The stick force per g, the stick displacement per g, the natural frequency, and the damping ratio varied with the amplitude of the response because of the non-linear C_m versus α of the basic F-94 airplane. The values shown are determined for an amplitude of response of 1.0 g for purposes of comparison. The decrease in natural frequency with amplitude, about an amplitude of +1.0 g incremental, was 0.1 cps per g at f_n = 0.42 cps. This decrease in frequency with amplitude was noticeable to the pilot primarily as a tuck-up tendency in the standard F-94. This tuck-up is defined by the pilot as a decrease in his F_s / n_z with increasing g

The first conclusion to be drawn from Figure 5 is that, within the range investigated, these opinions are consistent and form definite isopinion areas.

Probably the most interesting result is that the pilot's opinion rating reaches a maximum as the frequency is increased along a constant damping ratio and then decreases with increasing frequency. This occurs for all damping ratios, and is generally contrary to previous thinking on the subject which indicated that the all-important parameter was damping ratio - that as long as the damping ratio was favorable (about $\zeta = 0.7$), the pilot would probably like the system better with increasing frequency. The results of this investigation show a definite deterioration in opinion as the frequency is increased above $f_n = 0.6$ cps for a favorable damping ratio of $\zeta = 0.6$. The pilot comments as the frequency is increased above these values are: "Response too sensitive, too abrupt, stick zero too small and sensitive, pilot-induced oscillations". In the reference to "stick zero", the pilot is commenting on the force and position feel around trim. The "small and sensitive stick zero" refers to the initial response to small control inputs. When the natural frequency is high as in this case, the initial pitch acceleration, $\ddot{\theta}_0$, per stick force is high. Since the F_s/n_z and δ_s/n_z are kept constant, the initial pitch acceleration per stick motion is also high. Thus, the airplane response to small control inputs around trim is fast and abrupt. In tracking maneuvers, the pilot tends to overcontrol because of this abrupt and sensitive initial response. The subsequent out-of-phase (because of the high frequency) pilot inputs in trying to get back on target give rise to the comments on pilot-induced oscillations.

This observation that the pilot opinion decreases at higher frequencies, even for desirable damping ratios, is most important. Modern fighter airplanes are equipped with pitch dampers in recognition of the lack of adequate inherent aerodynamic pitch damping. It is suggested that a short period frequency reducer may be of equal importance in the realm of high speed flight. From the results of this program and that of Reference 2, it would be reasonable to expect that airplanes in which the short period natural frequencies much exceed 0.7 cps would be subject to pilot objections to their handling qualities. These objections might well be directed toward the elevator control system, but it would appear that extensive control system refinement could do little to improve the situation since the pilot would be, in reality, objecting to the high frequency short period. Much more fruitful results could be obtained by adding just one more input to the already-present elevator servo - an input proportional to the airplane response (α , n_z , or $\ddot{\theta}$) which would keep the short period natural frequency near the pilot's optimum throughout the maneuvering speed range of the airplane.

It is possible that a slight improvement can be made in the high frequency case by increasing the pilot's control motion per normal acceleration. It is felt that the improvement would be slight, if there is any improvement at all, because the pilot would object to the excessive control motion required to maneuver. An investigation of this possibility will be conducted in a forthcoming flight research program on this airplane.

The importance of frequency in the short period has been overlooked in the past primarily because of comparison with the "Dutch Roll" lateral mode of oscillation. Flight research at CAL and elsewhere has shown the effects of frequency in the "Dutch Roll" to be small. The two modes cannot be compared in this respect, however, because the pilot must maneuver the airplane through the longitudinal short period mode and its dynamics are always in evidence. Accelerations to change the flight path of the airplane are produced by lift forces generated by changing the angle of attack. The angle of attack change is produced by disturbing the short period. The "Dutch Roll" would never be disturbed, however, if the pilot had his way - his object is to minimize its appearance.

Returning to Figure 5, it is seen that as the frequency is decreased along a constant damping ratio, the pilot begins to object to the sluggish response, large stick zero, and initially heavy stick forces. The complaints of large stick zero and heavy forces arise from the nature of the pilot-airplane combination in that the pilot is in the feedback as well as the forward loop, comparing the actual response with the desired response and supplying additional inputs to minimize the difference between the two. In this case the pilot noting the slow response to his requirements (or commands) applies additional inputs to speed up the response. These additional inputs require larger forces and motions of the control stick. His additional inputs must be taken off as the desired steady state is approached, since the static F_s/n_z and δ_s/n_z have remained the same. Thus the pilot is quite sensitive to the maneuvering -or transient- forces which are required to make the airplane response match his requirements. It is sometimes difficult from the pilot's stick force comments alone to differentiate between heavy forces and normal response, and normal forces and sluggish response.

In the low damping ratio, moderate frequency area of Figure 5, the pilot objects to oscillations in the airplane response. Comments indicate that this tendency is particularly objectionable in rough air, as would be expected since the rough air excites the short period mode. The pilot also comments on an inability to trim the airplane because of the oscillations induced by his inputs as well as the atmospheric turbulence. The response is initially somewhat abrupt and then overshoots the desired final value, oscillating at a frequency which is difficult for the pilot to follow and damp out. In the very low damping ratio and high natural frequency cases, the pilot-airplane combination actually became unstable (while the airplane-alone was still stable) and the pilot was forced to let go of the stick and let the oscillation damp out of its own accord. The pilot-airplane combination becomes unstable because of phase lags within the pilot in supplying corrective inputs. These lags in his position feedback result in inputs in phase with negative damping. These inputs wipe out the small amount of positive damping in the airplane causing the aforementioned instability of the pilot-airplane combination.

As the damping ratio is increased along a moderate natural frequency, the oscillation tendency decreases, the initial response becomes less abrupt, and the pilot's opinion increases to a maximum around a damping ratio of from $\zeta = .55$ to $\zeta = .70$. If the damping ratio is further increased above $\zeta = 1.0$, the response becomes sluggish, the stick forces are heavy, and the stick motion to maneuver is increased.

In the region of high damping ratio, high natural frequency, the deterioration of pilot opinion can be traced to an overlap of bad features of the adjacent regions: high ζ, moderate ω_n, and moderate, ζ, high ω_n. In the high ζ, moderate ω_n region, the objection is slow response time with the attendant heavy forces and large stick motion to maneuver. In the moderate ζ, high ω_n region, the pilot objects to the abrupt initial response, sensitive and small stick zero, and light forces around trim. For a response in the first region, if ω_n is increased to improve the response time, the initial response becomes too abrupt and sensitive before the over-all response time becomes desirable. Thus, if the natural frequency and the damping ratio are increased together in a constant ratio (giving a nearly constant response time) from the "best tested" region, the pilot will begin to object to the abruptness of the initial response. This comment was not consistently given in this evaluation because the servo phase lags reduced the initial pitch acceleration per stick force below that experienced with a no-lag, purely second-order short period response. He did, however, object to the fact that the response starts quickly and then slows down, requiring additional control over and above that indicated by the initial response. This departure of the shape of a particular response from the shape of his desired response can be measured at high damping ratios by the ratio of the time for the response to reach a large percentage (say 74%) of its final value to the time for it to reach a small percentage of its final value (say 20%). It can be shown that this time ratio, t_2/t_1, is independent of the natural frequency and depends only upon the damping ratio, ζ.

In the region of low ζ, low ω_n, the pilot comments again indicate an overlap of the objections of the adjacent areas. He objects to the slow initial response, the increase in rate of response after the initial response, the overshoot, and the oscillation. The airplane-alone response starts slowly, then increases in rate and overshoots. The pilot, noting the slow initial response, adds extra input at about the time the response starts to increase rapidly in rate. This adds to the overshoot of the airplane-alone, making it difficult to control the load factor within limits while maneuvering. The frequency of oscillation is slow enough that the pilot can keep up with the airplane but this requires careful control and constant attention. Any oscillations that are induced require a relatively long time to die out and, in rough air, the airplane would appear to be in almost constant oscillation.

The pilot objections discussed above are summarized in Figure 6. In this figure, the objections are grouped in the regions of ζ and f_n where they are prevalent.

In Figure 7, the isopinion area of Acceptable Good has been bounded by curves based on certain characteristics of the airplane-alone response. These characteristics are felt to be a representative measure, in terms of what he senses, of certain objections of the pilot to the handling qualities in that region of ζ and f_n . The following is a list of these characteristics as associated with the response of a second order system (the airplane short period response) to a step function input (pilot-applied step force input). Alongside the characteristic is listed the common pilot comments. Figure 8 shows typical step responses with the symbols defined.

PILOT COMMENTS ON	CHARACTERISTIC
1) INITIAL RESPONSE	Initial pitch acceleration per stick force
2) OSCILLATION IN AIRPLANE	Transient peak ratio
3) INITIAL RESPONSE COMPARED TO FINAL RESPONSE	$\frac{\text{Time to 74\%}}{\text{Time to 20\%}}$
4) TIME TO SETTLE DOWN	Response time (time to 95%)

In the range of acceptable damping ratios, the limits on the natural frequency appear in the pilot comments as objections to the initial response to control application - it is either too abrupt or too sluggish. Representing this initial response by initial pitch acceleration per stick force, $\ddot{\theta}_o / F_s$, it is seen in Figure 7 that lines of constant $\ddot{\theta}_o / F_s$ tend to approximate the opinion boundaries in this region. Due to the lags inherent in the servo system, these lines of constant $\ddot{\theta}_o / F_s$ bend upward at higher damping ratios. In a purely second-order short period response, $\ddot{\theta}_o / F_s$ varies only with ω_n for a constant F_s / n_z and would appear as a horizontal straight line in Figure 7. This would indicate that if the servo lags were reduced, more nearly simulating an actual short period, the upward tilt of the isopinion areas of Figure 5 would be reduced, and the dotted contour more positively closed.

In the range of acceptable ω_n, there exists an upper and lower limit on damping ratio. If ζ is low, the pilot objects to oscillations in the airplane, tracking difficulties, and control difficulties in rough air. The pilot sees the amplitude of one response peak compared to the next, following a disturbance. This is represented by the transient peak ratio, TPR, and has a lower limit in the Acceptable Good Region of 0.21. This corresponds to $\zeta = .45$. The upper limit on ζ comes from the pilot objections to the slowness of the final response compared to the initial response. The ratio of the time to 74% of final value, t_2, to the time to 20%, t_1, varies only with ζ and has a maximum value of approximately 3.2 in the Acceptable Good region.

Another parameter the pilot sees and is sensitive to is the response time or the time it takes for a response to settle down following a disturbance. Defining response time, RT, as the time it takes the envelope of the response to reach 95% of its final value, the maximum desirable RT in the Acceptable Good region is $RT = 2.6$ seconds.

The only open area is at the high ζ, high ω_n end. This area is closed, as mentioned before, by the overlap of the adjacent objections. If there were no servo lags, the $\ddot{\theta}_o / F_s$ line would, rotate until horizontal, closing off the Acceptable Good area earlier than shown from this investigation.

EVALUATION OF STICK FORCE AND STICK DISPLACEMENT PER NORMAL ACCELERATION AT CONSTANT SHORT PERIOD DYNAMICS

The results of the stick force and stick motion evaluation are shown in Figure 9 as a plot of pilot opinion as a function of stick force per g and stick displacement per g. During this evaluation, the airplane short period dynamics were maintained nearly constant and at the values for a standard F-94 at that speed and altitude.

The variations in short period dynamics which took place were due to the cg movement with fuel consumption. Artificial stability was introduced as a function of fuel remaining as the evaluations progressed in order to keep the natural frequency constant. The maximum variation in short period dynamics was from $\zeta = .68$ and $f_n = .38$ cps to $\zeta = .56$ and $f_n = .44$ cps. Tracing this variation for constant $\zeta\omega_n$ on the short period evaluation plot in Figure 5, it is seen that all points in this range lie in the Acceptable Good region. It is not likely that the above variations in short period dynamics caused much change in the pilot's opinion during the stick force and stick position evaluations.

The evaluation maneuvers were the same as those used in the short period, and the evaluation time was the same. The repeatability of the pilot's opinion was not as good as on the short period evaluation. This could be due to the pilot using a rating scale which evolved from the short period work and was, perhaps, too fine a breakdown of his opinion.

The over-all results are consistent and a definite pattern is formed by the varying pilot opinion. A study of the pilot comments during the evaluation as well as his over-all ratings indicate the following general conclusions. It should be noted again that these comments and opinions refer to a fighter class of airplane and are limited to the speed range for maneuvering - no landing or takeoff condition maneuvers were included in the evaluations.

The best-tested area was around 8 lb/g and 0.20 inches per g. The pilot reported the force feel was good, both around trim and for maneuvering. The stick motion was satisfactory and the "stick zero" was good. The response of the airplane was good - fast but not abrupt.

If the stick displacement per g is held constant at about .20 inches per g and the stick force per g is increased, the pilot objects to the heavy forces and the sluggish response. If the forces are reduced below 8 lb/g, the pilot objects to the light forces, very sensitive response to control, tendency to overcontrol, and pilot-induced oscillations. The comments about the response as the stick force per g is varied appear to be reasonable when the pilot-airplane combination is viewed as a closed loop system. The pilot closes the loop by acting as the feedback element as well as a direct path element. In varying the F_S/n_z, the direct path gain is being varied. This, in turn, varies the dynamics of the closed loop response. This is just what the pilot says in his comments. When the F_S/n_z is reduced (the direct path gain n_z / F_s is increased) the response becomes oscillatory, too sensitive, and the pilot has a tendency to overcontrol. Conversely, if the F_s / n_z is increased (the direct path gain, n_z / F_s, is reduced) the response becomes sluggish and slow.

The stick motion comments cannot be so neatly tied down because it is not as clear just how stick motion is used by the pilot. Apparently, the stick motion acts as a filter on the pilots force inputs and introduces some lag into his inputs. The lag arises because the pilot has to move his arm to apply the desired amount of stick force.

A certain amount of motion is desirable in the maneuvering speed range - about 0.2 inches per g. If the motion is reduced, it has the effect of reducing the filtering action on the input forces. The force inputs are sharper and more abrupt, and this gives a quicker and more abrupt response. The pilot objects mildly to this abruptness, and substitutes a heavier force level (which slows the over-all response down) for the filtering or smoothing action of the stick motion. This is evidenced by the slight curving to the right of the isopinion boundaries of Figure 9 as the stick motion is reduced below his desired value.

A most interesting result of the force and position evaluation was that the pilot can do a very good job of flying the airplane at speeds above that for landing with no stick motion at all. The pilot has no difficulty in recognizing the lack of motion, and he always qualified his maneuvering speed comments with the reservation about preferring stick motion for takeoff and landing; but his comments indicate that the lack of motion had little effect on his ability to accurately maneuver the airplane and use it as a weapon.

As the motion is increased above 0.2 inches per g, the pilot's opinion begins to decrease. There are two effects here. First, the pilot apparently has a minimum desirable spring rate on the stick. Even though the F_s / n_z is at the desirable level, when the motion gets large the feel of the stick itself (δ_s / F_s) becomes poor. The pilot objects to the slow rate of increase of the force with displacement as the stick is moved away from trim.

The other effect is that of the increased lag or smoothing due to the large stick motions. He actually has to move his hand and arm in order to apply forces to the stick, and this requires a certain additional time as the motion per pound is increased. Verification of this conclusion is difficult from the pilot's comments. When he objects to the excess stick motion, he just says he doesn't like it with little or no reason why he doesn't.

However, with the very large motion (0.6 in/g) he began to object to a difficulty in tracking the ground target during the simulated strafing run. He complained of having to "pump the stick back and forth to stay on the target". The steady maneuvers, like steady turns, were satisfactory; the difficulty arose when trying to make rapid corrections such as during a tracking run. This would seem to be a problem of dynamics - excess lag in the response to his rapid inputs caused by the excessive stick motion.

It will be noticed in Figure 9 that the opinion boundaries appear to curve somewhat to the right as the motion is increased to large values. This curvature is believed to be due to the compromise between stick spring rate, δ_s / F_s, and stick force per g. The opinion gets worse as the motion is increased much above .25 inches/g; but, the best opinion at the higher δ_s / n_z is obtained by having a slightly heavier than optimum F_s / n_z with the attendant better spring rate δ_s / F_s. The pilot commented that he could tolerate the large stick motions a little better with slightly heavier than optimum stick force per g.

INTERACTION EVALUATION

A very brief evaluation of several stick forces per g was conducted at three additional values of short period dynamics.

The primary reason for this evaluation was to determine if some of the deterioration of opinion in the short period evaluation was due to the particular values of F_s / n_z and δ_s / n_z at which the evaluation was conducted. The values used in the short period evaluation were picked by the pilot as desirable and slightly heavy at the F-94 short period dynamics. Thereafter the F_s / n_z and δ_s / n_z were held constant at these values while ζ and ω_n were varied. As the evaluation progressed, the pilot complained of heavy forces and large stick motion in the sluggish response region and light forces in the quick or abrupt response region.

The interaction between F_s / n_z and short period dynamics was investigated in three regions: low ζ, low ω_n; low ζ, high ω_n; and high ζ, moderate ω_n. The first was a region of slow initial response with a slow oscillation tendency, the second was a region of abrupt initial response with pilot-induced oscillations, and the third was a region of slow and sluggish response. The values were chosen to be in an Acceptable to Acceptable Poor region where the objection was prominent but not overpowering:

1) $\zeta = .40, \quad f_n = .32$ cps
2) $\zeta = .40, \quad f_n = .62$ cps
3) $\zeta = 1.6, \quad f_n = .48$ cps

Inasmuch as very little data were obtained, the absolute rating of each point was not substantiated. The short period evaluation showed that a large sample of data was necessary before conclusions could be drawn based upon absolute ratings. However, analysis of the pilot's comments indicates that he is more reliable in giving relative comparisons on the same flight. In view of these considerations, the only valid conclusions which may be drawn from this evaluation are those based upon the trend of the pilot opinion data on one flight.

The results of this investigation are plotted in Figures 10a, 10b. 10c, and 10d as pilot opinion versus stick force per g for the three values of ζ and ω_n. In these figures the pilot opinion of the particular combination of period and damping is taken from the short period evaluation and shown shaded for the maximum excursion of F_s / n_z during the short period evaluation.

Figures 10a and 10d have ratings in the shaded area, indicating them to be fairly representative opinions as determined from the large quantity of data amassed during the short period evaluations. The trend of the data in Figure 10b seems consistent, but the level of the opinion is high in the shaded region compared to the short period evaluations. Similarly, the ratings in Figure 10c are slightly higher than during the short period evaluations.

It is noteworthy that the increase of opinion outside the shaded area is small except in Figure 10c, the high ζ , moderate ω_n point. This would indicate that in the low damping ratio regions the pilot opinion ratings of the short period evaluation are given for nearly-optimum values of F_s/n_z The seemingly apparent trend in Figure 10c is negated somewhat by the data of Figure 10d for about the same ζ and ω_n but covering a lower range of F_s/n_z . However, it does appear that the pilot prefers somewhat lighter F_s/n_z in the high ζ , moderate ω_n region, and his opinion of the dynamics might be improved slightly by decreasing the F_s/n_z below that of the short period evaluation.

One further question remained - would decreasing the objectionable stick motion of the high ζ , moderate ω_n , and the low ζ , low ω_n regions improve the pilot's opinion of those short period dynamics? These conditions were set up with F_s/n_z at desirable values. The pilot evaluated two stick motions for each condition: normal motion of approximately 0.22 inches/g and less-than-normal motion of 0.15 inches/g. For the high ζ , moderate ω_n point, the pilot preferred the smaller motion but commented that its effect was not great enough to change his rating from that given the normal stick motion. For the low ζ , low ω_n point, decreasing the stick motion increased the oscillation tendency causing the pilot to decrease the rating very slightly from "Acceptable Poor, plus" to "Acceptable Poor, with a possible plus".

It is believed that the interaction evaluation, although brief, did indicate the following conclusions:

1. The pilot objections to the stick force and motion feel in the short period evaluations were the result of the effects of the varying dynamics on the pilot-airplane combination.
2. In the region of high ζ , moderate ω_n , the pilot opinion rating may be increased slightly by decreasing the F_s/n_z and δ_s/n_z somewhat below the values used in the short period evaluation. Otherwise, little improvement can be made in the pilot ratings of the short period shown in Figure 5 by varying the F_s/n_z and δ_s/n_z .

CONCLUSIONS AND RECOMMENDATIONS

It is concluded that:

1. Consistent pilot opinion ratings were obtained for a range of short period dynamics and stick force and displacement gradients. These ratings form areas of varying degrees of pilot acceptance of the resultant handling qualities.
2. The short period natural frequency emerged as a parameter of importance comparable to that of the damping ratio in determining the pilot's opinion of the longitudinal handling qualities. Too high a natural frequency, even with a desirable damping ratio, causes serious pilot objections. These objections may be directed toward the control system when, in reality, they arise from the high short period natural frequency. It is unlikely that control system refinement will alleviate this difficulty. It will probably be necessary to reduce the natural frequency of the longitudinal response in high-speed flight as well as to supplement the inherent airplane short period damping.
3. A brief evaluation was conducted to determine the effects of the short period dynamics on the pilot's ratings of the force feel. Little improvement could be made in the over-all rating by changing the stick force gradient except in the high ζ , moderate ω_n region where the pilot preferred somewhat lighter F_s / n_z and smaller δ_s / n_z .

It is recommended that:

1. The effects of varying amounts of breakout force on the pilot's ratings be determined.
2. The short period evaluations be extended to higher natural frequencies to determine the minimum acceptable boundary.
3. An evaluation be conducted to determine the effect of short period dynamics and stick force and displacement gradients on the pilot's opinion in the landing configuration.

4. The ratings established by one pilot be verified by a limited number of additional pilots.

APPENDIX

DETERMINATION OF CALIBRATION GRID

A brief description is given of the method used to obtain the short period damping ratio and natural frequency associated with each pilot evaluation.

Each time history of the normal acceleration response to a pulse elevator input was analyzed as a free oscillation to obtain a ζ and ω_n for the best second-order fit to the time history. The methods used are described in Chapter 19, Table 19-2 of Reference 5.

It was observed that the values of ζ and ω_n calculated from the pulse responses of the unstabilized airplane ($\delta_e/_\alpha = \delta_e/_{\dot\alpha} = 0$) varied with the amplitude of the response. By obtaining several pulse responses of various amplitudes at the same values of fuel remaining, it was found that the ratio of the short period damping to the moment of inertia (i. e., $2\zeta\omega_n$) remained constant while ω_n varied. This was attributed to a non-linear variation of C_m with α . The mean amplitude of normal acceleration for all the response data was calculated to be 1.0 g. The following first-order frequency correction was determined to reduce the measured data to that of a common amplitude of response.

$$f_{n_{1.0g}} = f_{n_{meas.}} + .106\,(\Delta n_z - 1.0)$$

Converting this to a "stiffness" correction:

$$\Delta f^2_{n_{ampl.}} = f^2_{n_{1.0g}} - f^2_{n_{meas.}}$$

$$= .212\, f_{n_{meas.}} (\Delta n_z - 1.0) + [.106\,(\Delta n_z - 1.0)]^2$$

The variation of C_{m_α} with fuel remaining was determined from the unstabilized airplane values of ζ and ω_n (corrected to 1.0 g amplitude) by plotting ω_n versus fuel remaining. A reference value of fuel remaining of 350 gallons was chosen for constructing the gridwork. The stiffness correction for a 1.0 g response was the difference between the square of the natural frequency of the unstabilized airplane and the square of that frequency for 350 gallons fuel remaining.

$$\Delta f^2_{n_{F.R.}} = f^2_{n_{350\,gal.}} - f^2_{n_{F.R.}}$$

An assumption was next made that:

$$f_{n_{1.0g}}{}_{350\,gal.} = \sqrt{f^2_{n_{meas.}} + \Delta f^2_{n_{F.R.}} + \Delta f^2_{n_{ampl.}}}$$

This is strictly true only if the artificial stability gains are zero since the Δ's are determined for the unstabilized airplane. If the gains are not zero, the phase lags in the stabilization equipment introduce errors. Several calculations showed the effect of these lags to be small and the equation above was used to reduce all the experimental values of ζ and f_n to the values they would have had if the fuel remaining had been equal to 350 gallons and the amplitude of response had been 1.0 g.

With these corrected values, a grid of lines of constant ζ and f_n was superimposed upon the scale of δ_e/α and $\delta_e/\dot{\alpha}$. However, it was somewhat difficult to fair these lines for high values of ζ, primarily due to the reduced accuracy in determining f_n and ζ from the transient response for high ζ.

In order to more accurately determine the shape of the grid, the corrected values of ζ and f_n were compared to a theoretical gridwork shown in Figure 11. This gridwork is based upon an analysis of the response of the stabilized airplane to pilot-supplied inputs. The response is sixth order, and the gridwork shows the variation of the ζ and f_n associated with the airplane short period roots of the sixth-order response as δ_e / α and $\delta_e / \dot{\alpha}$ are varied. A detailed description of the determination of these roots is contained in the Appendix of Reference 2.

The comparison was generally good, but some differences did exist. So, for the values of δ_e / α and $\delta_e / \dot{\alpha}$ corresponding to each experimental point, the differences $\Delta \zeta$ and Δf_n between the theoretical values and the corrected experimental values of ζ and f_n were determined. The values of $\Delta \zeta$ and Δf_n were plotted versus ζ and f_n and also versus δ_e / α and $\delta_e / \dot{\alpha}$ to determine if the differences were functions of these parameters. These plots indicated the differences to be linear functions of ζ and f_n. Thus, if the theoretical gridwork could be shifted and rotated an amount indicated by the experimental data, a calibration grid of ζ and f_n could be obtained in which the experimental inaccuracies were minimized.

This was accomplished by a least squares analysis assuming corrections to the theoretical grid of Figure 11 of the form:

$$\Delta f_n = C_0 + C_1 f_n + C_2 \zeta$$

$$\Delta \zeta = C_3 + C_4 f_n + C_5 \zeta$$

The actual difference between the theoretical grid and the test point was denoted by Δf_{n_k} and $\Delta \zeta_k$. Then the sums of the squares $(\Delta f_n - \Delta f_{n_k})^2$ and $(\Delta \zeta - \Delta \zeta_k)^2$ were minimized by setting equal to zero the partial derivatives of these sums with respect to each of C_1, C_2, C_3, C_4, and C_5.

From the resulting equations, the "best" values of C_1, C_2, C_3, C_4, and C_5 were determined. Using these values, the best $\Delta \zeta$ and Δf_n were determined as functions of the theoretical ζ and f_n.

A new grid was constructed by shifting the theoretical grid by the amounts Δf_n and $\Delta \zeta$ determined from the least squares analyses. This grid is shown in Figure 12.

The values of ζ and f_n associated with the pilot evaluations were determined by applying a correction to the values from Figure 12 for the difference in "stiffness" between that for the actual fuel remaining and that for 350 gallons.

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5. Draper, C.S., McKay, W., and Lees, S. Instrument Engineering, Volume II. McGraw Hill Book Co., Inc. September 1952

Figure 1 EF-94A AIRPLANE, AF SERIAL NO. 49-2500

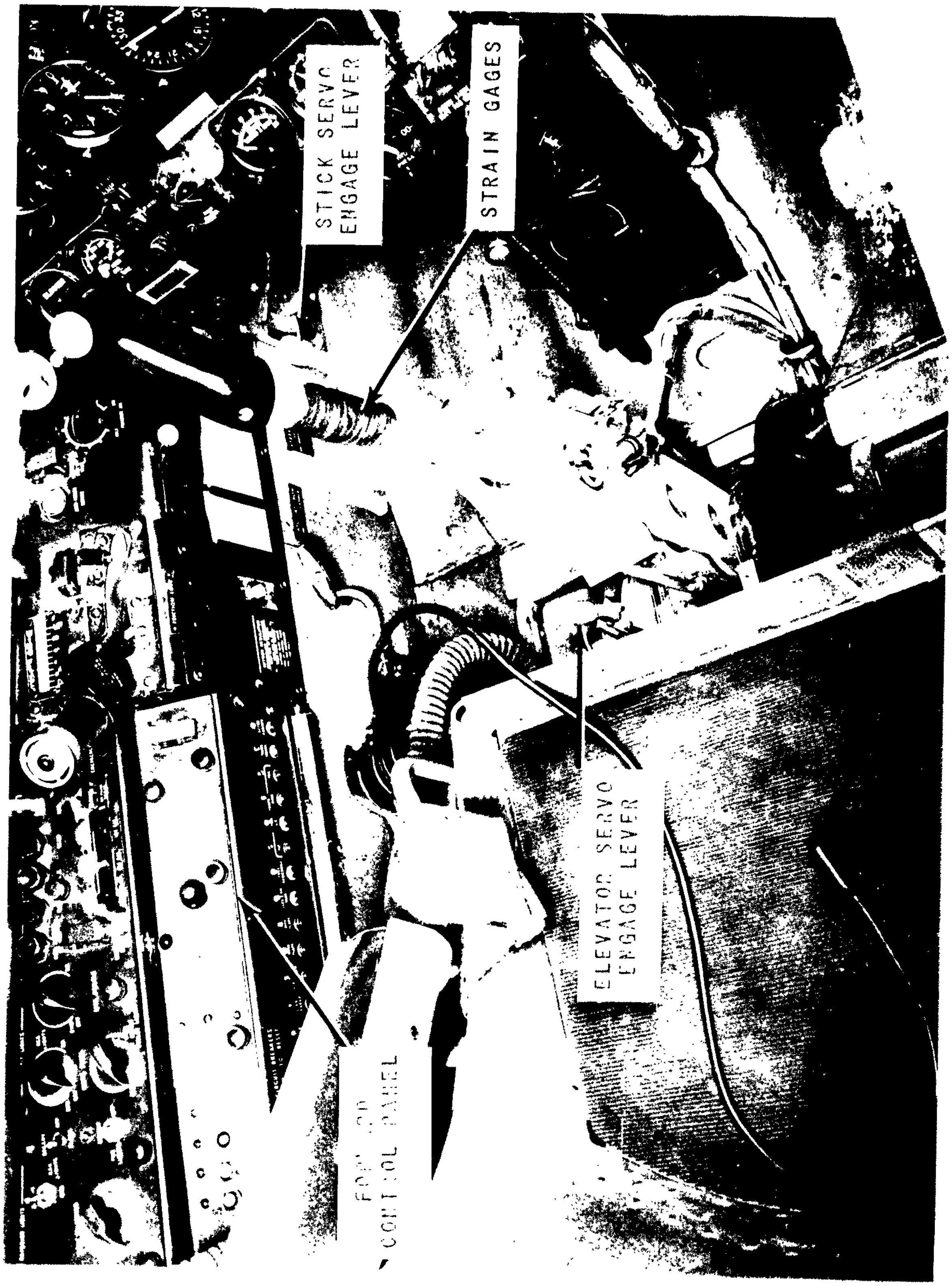


Figure 2 FORWARD COCKPIT

Figure 3 AFT COCKPIT

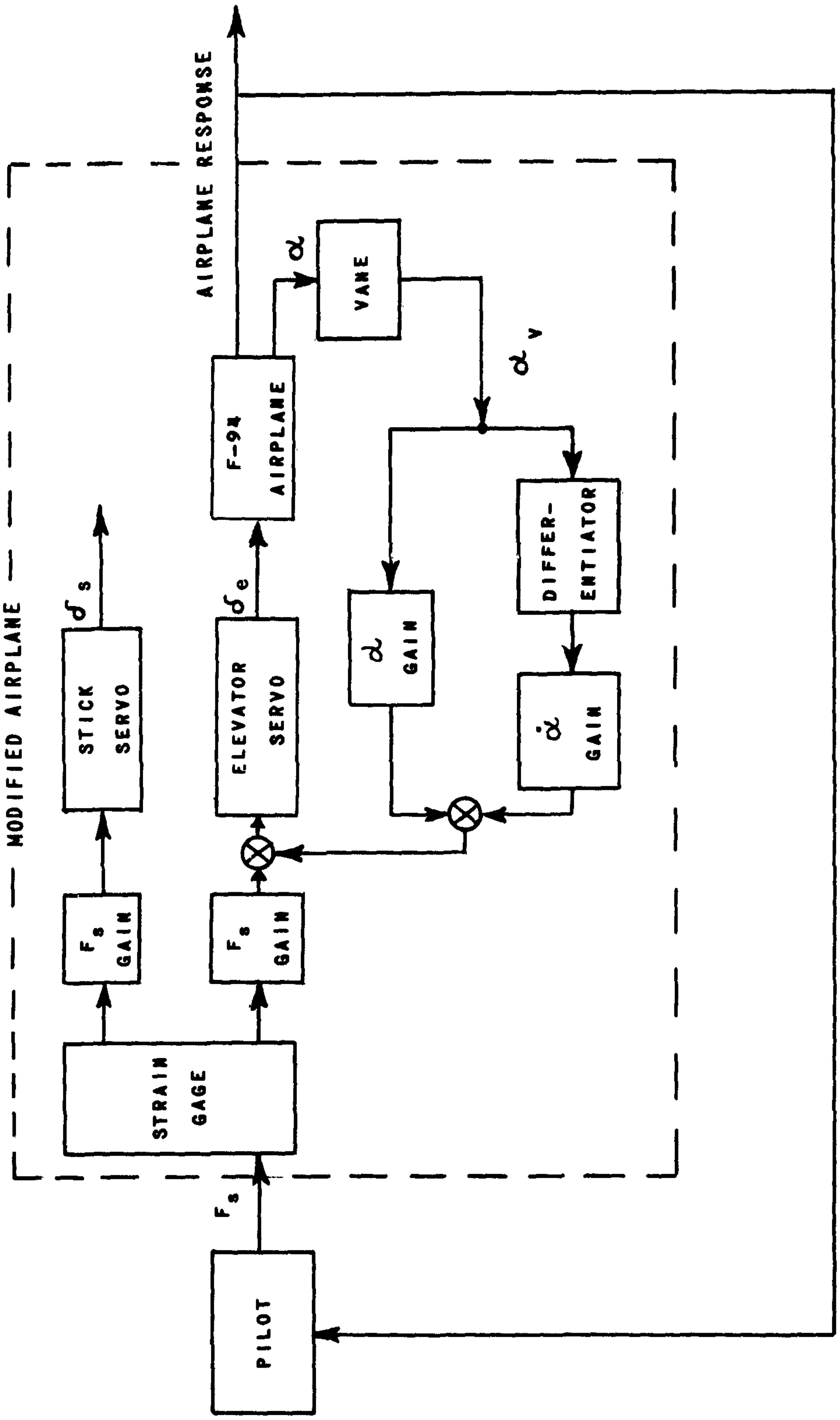


Figure 4 VARIABLE-STABILITY F-94 SCHEMATIC DIAGRAM

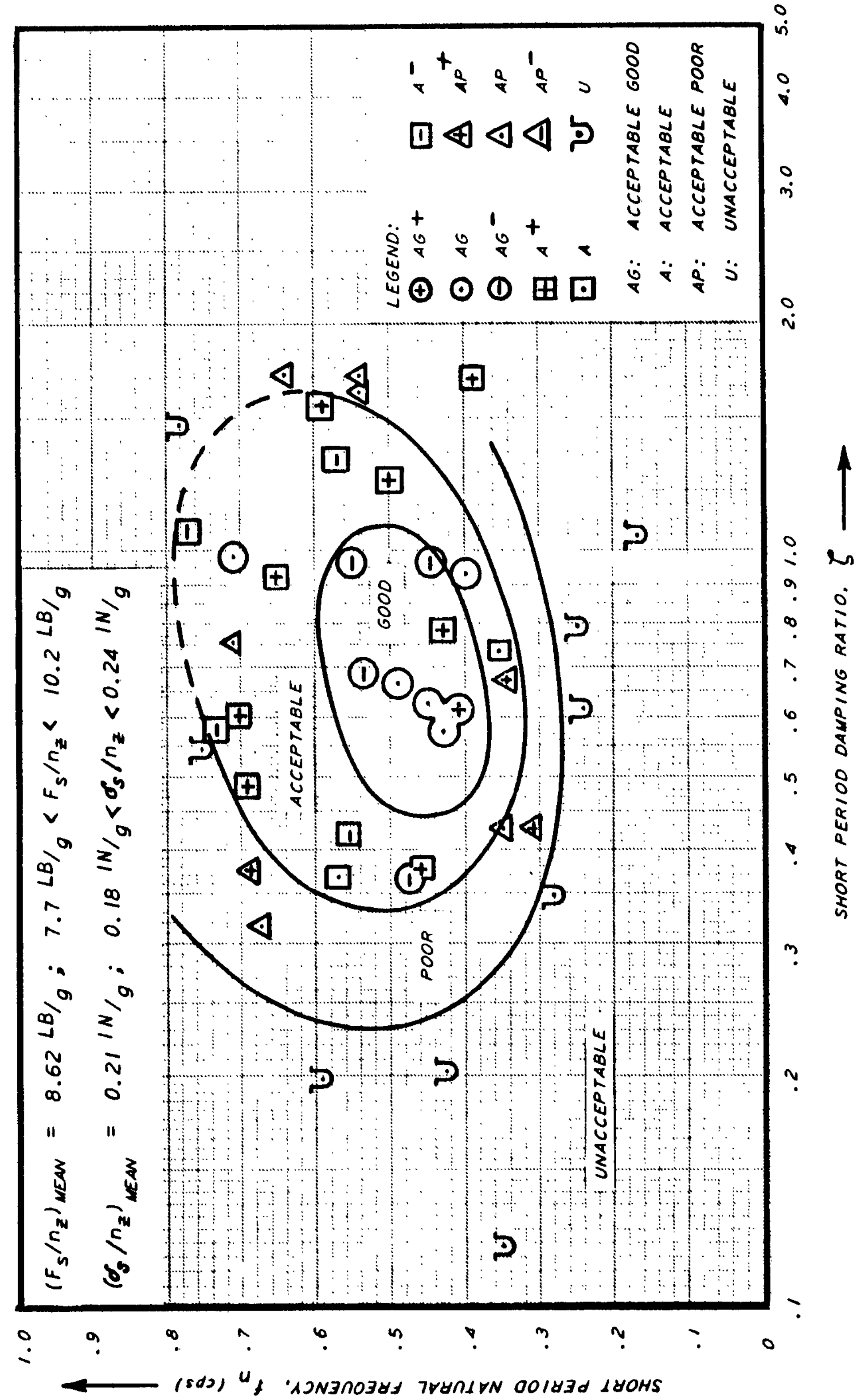


Figure 5 SHORT PERIOD PILOT OPINION RATINGS

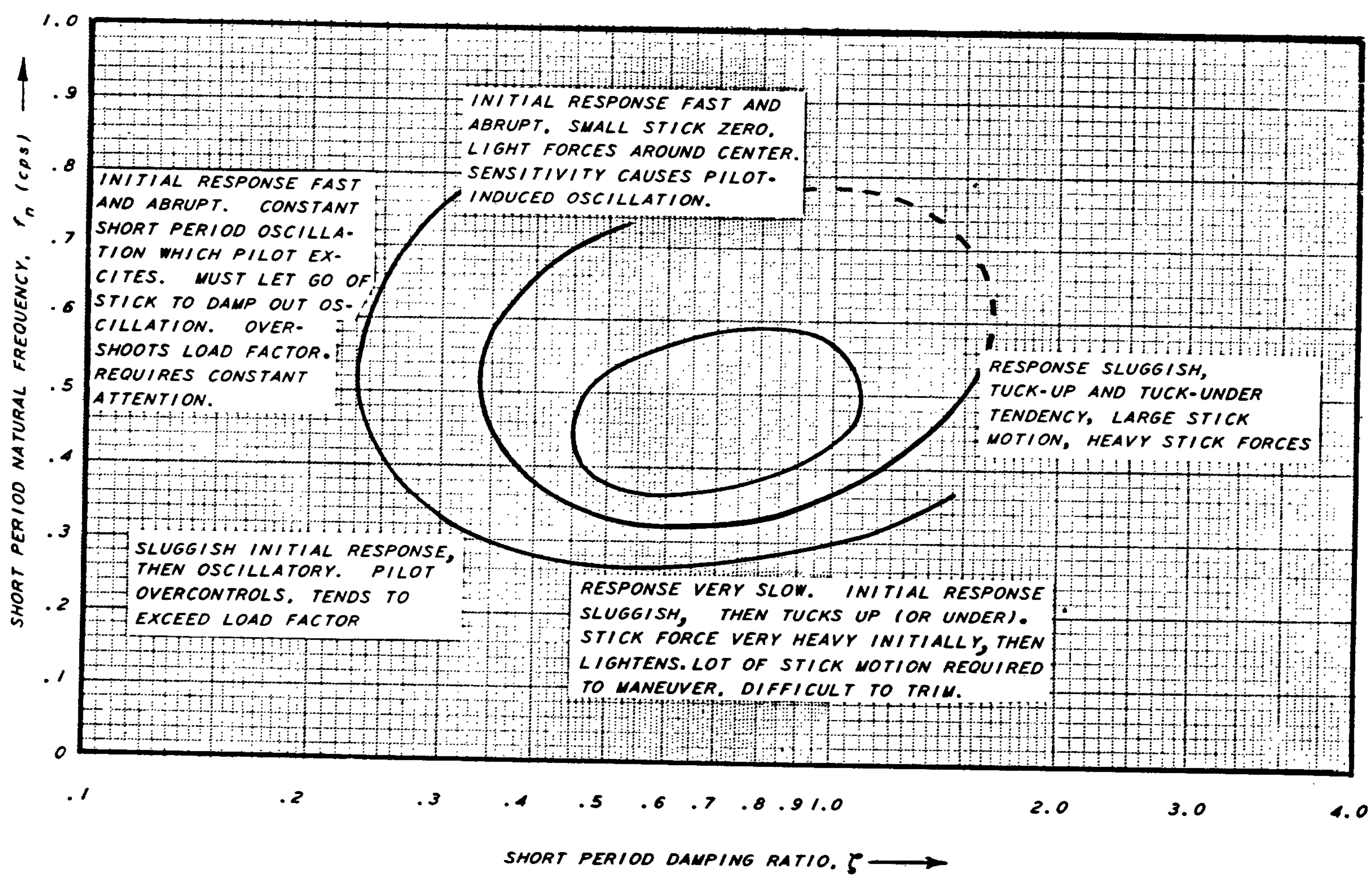


Figure 6 PILOT OBJECTIONS TO VARIOUS SHORT PERIOD DYNAMICS

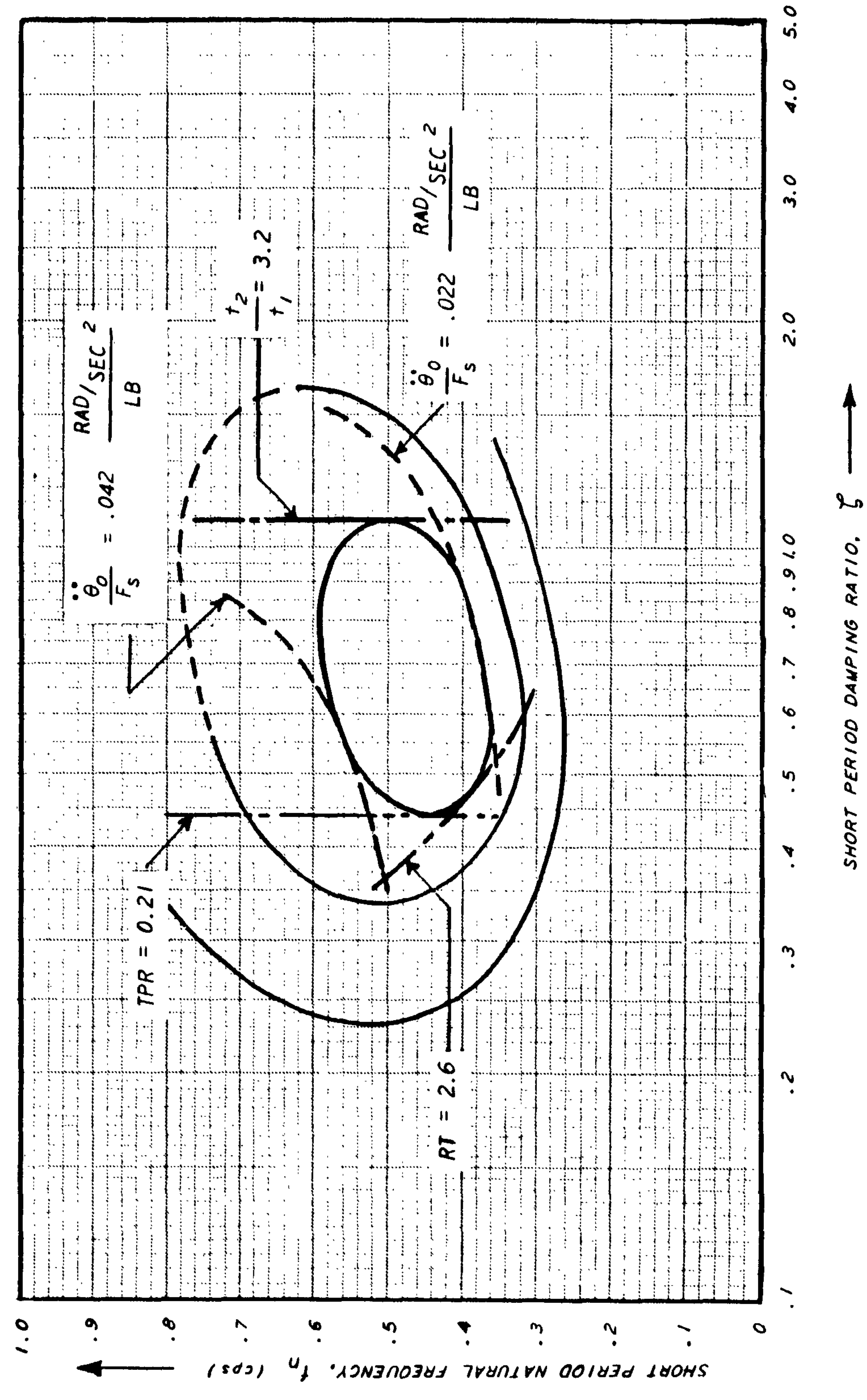


Figure 7 APPROXIMATION OF OPINION BOUNDARY WITH LIMITING RESPONSE PARAMETERS

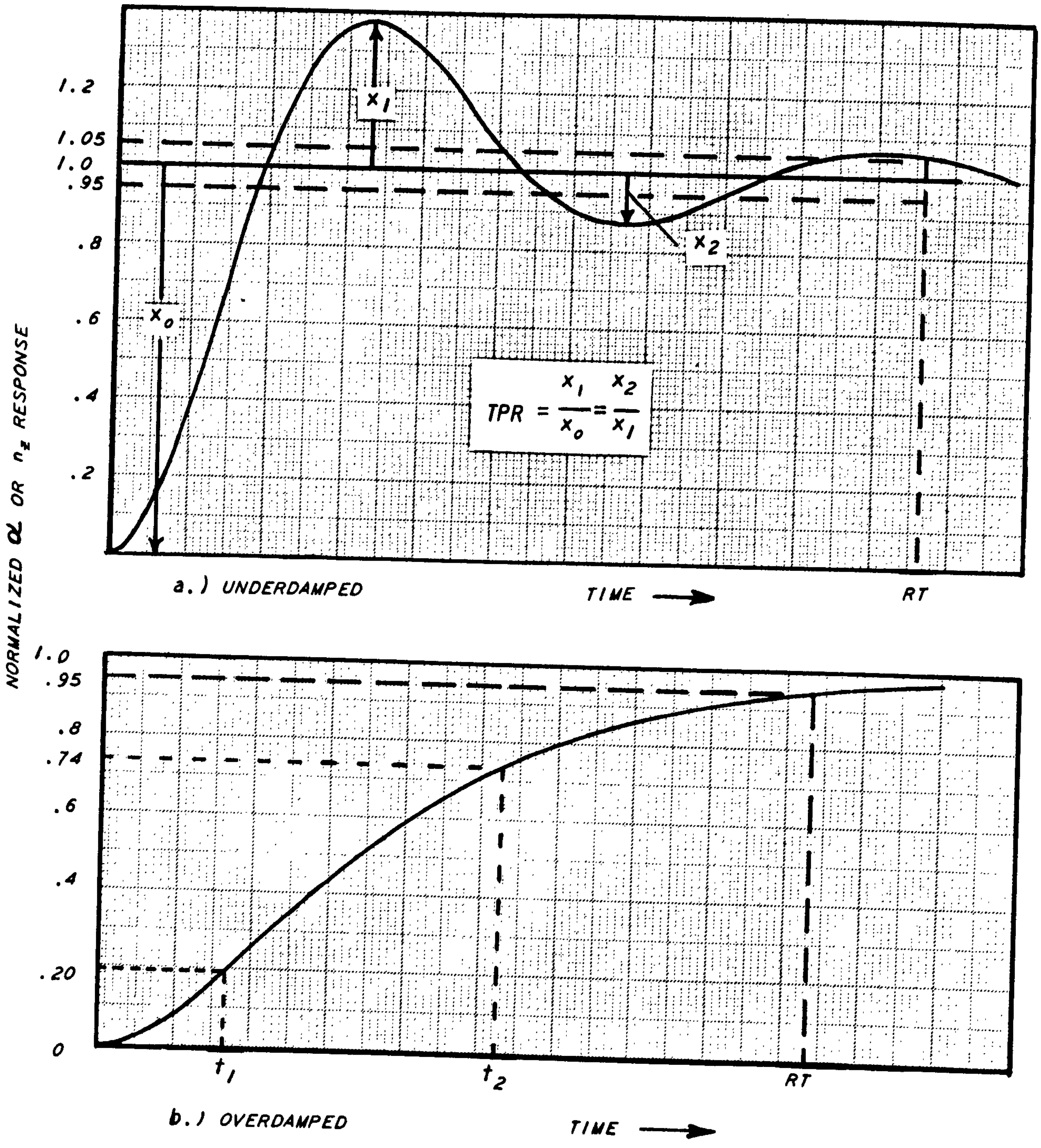


Figure 8 TYPICAL SHORT PERIOD RESPONSES TO AN ELEVATOR STEP INPUT

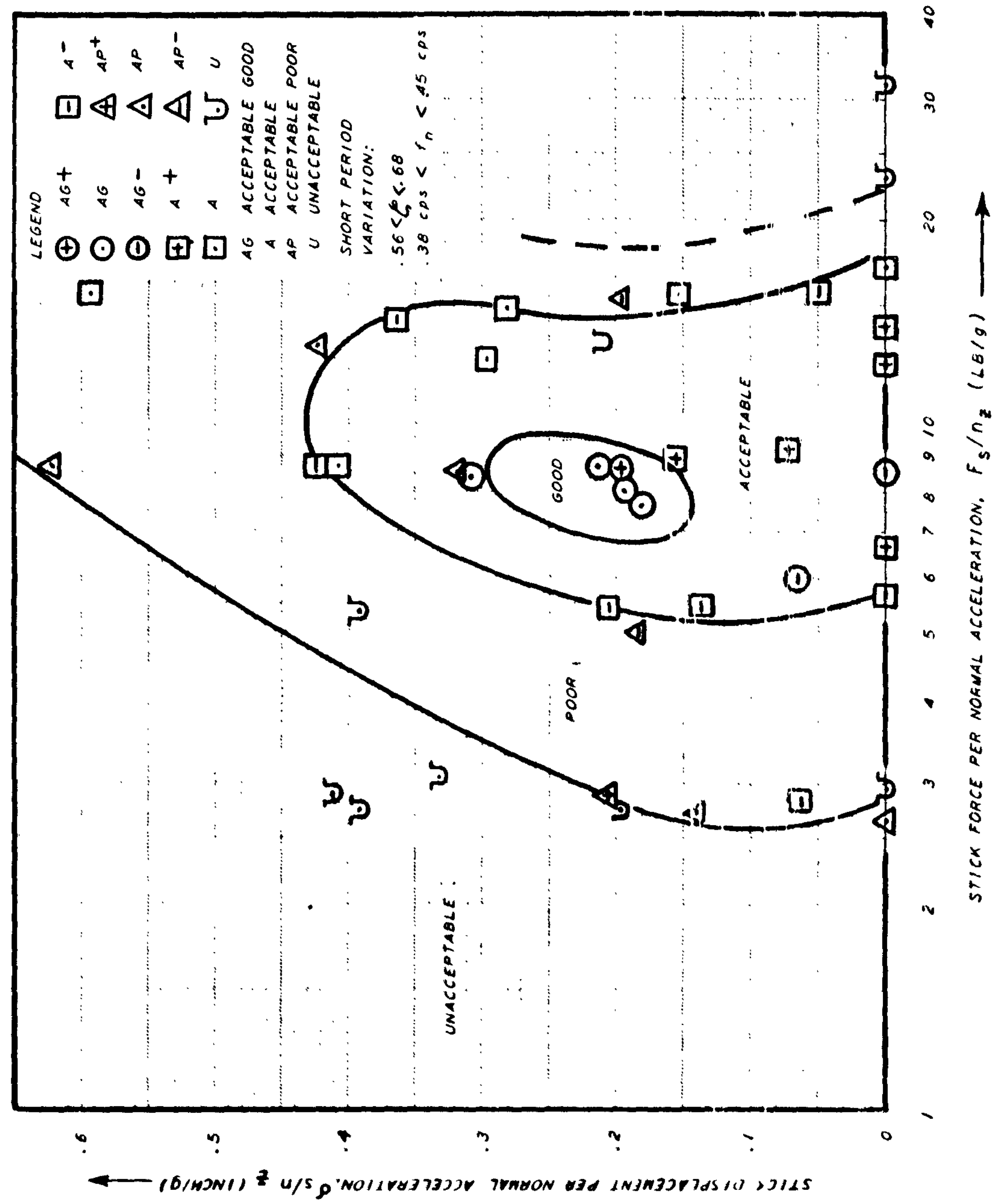
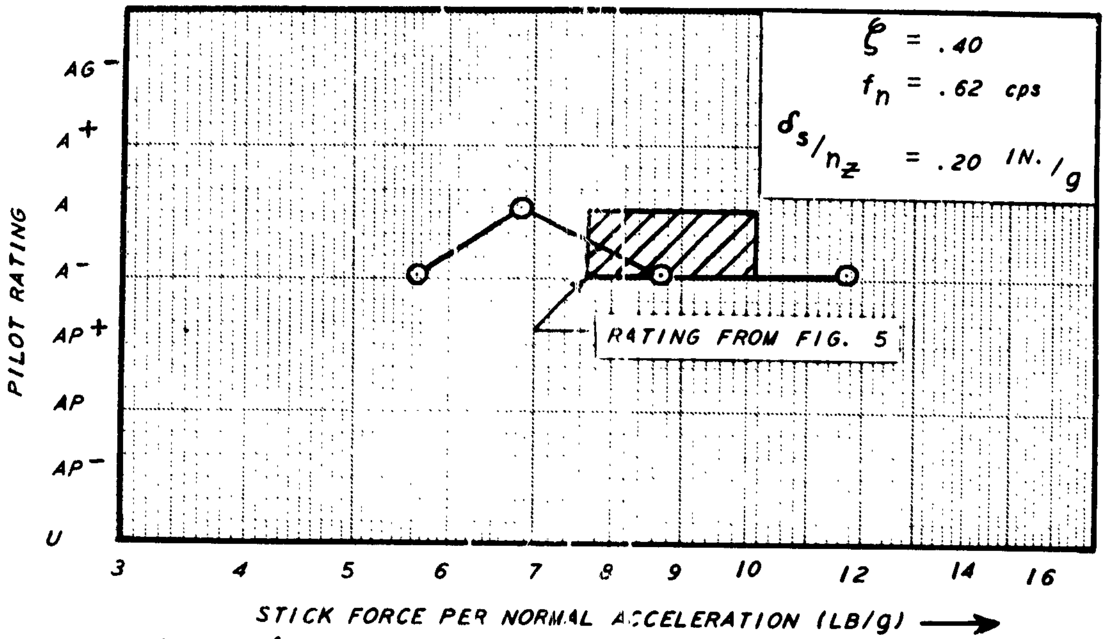
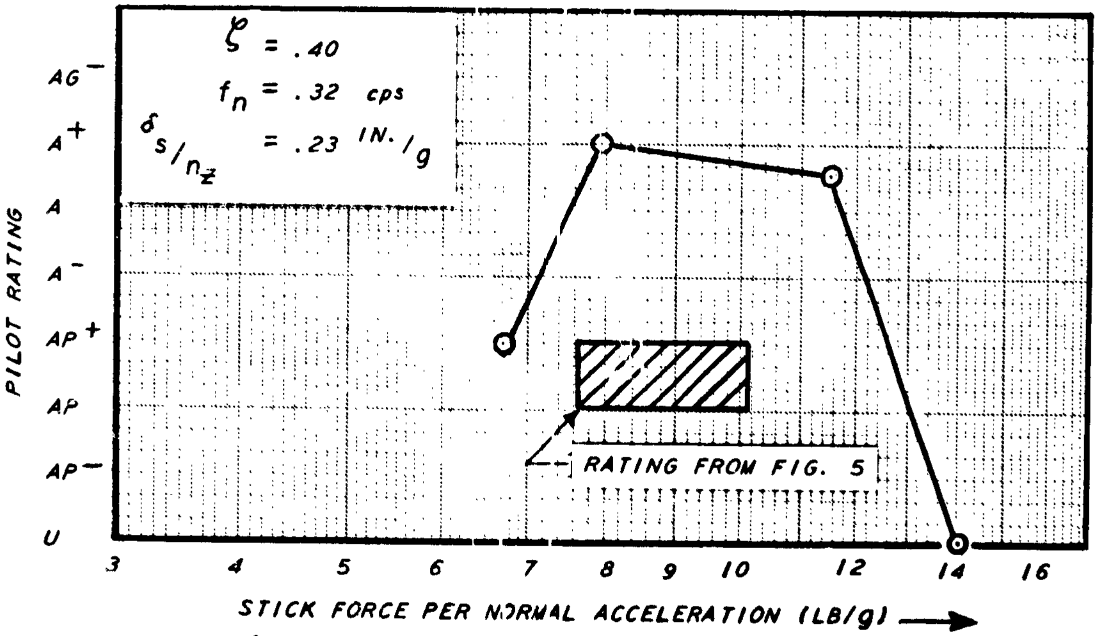


Figure 9 STICK FORCE AND STICK DISPLACEMENT PILOT OPINION RATINGS

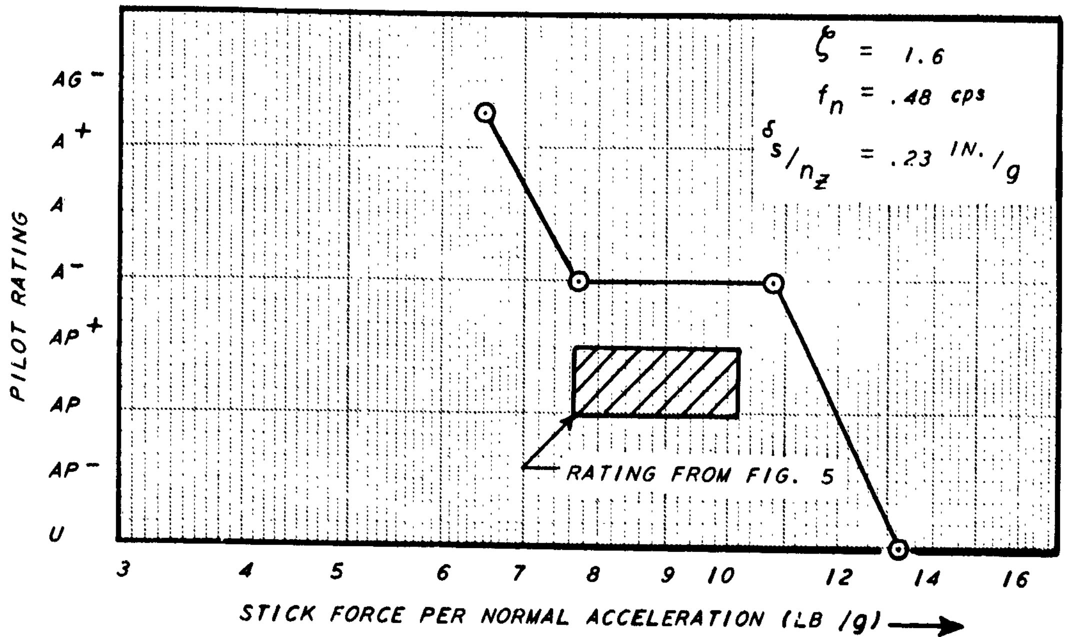


a.) LOW ζ HIGH ω_n

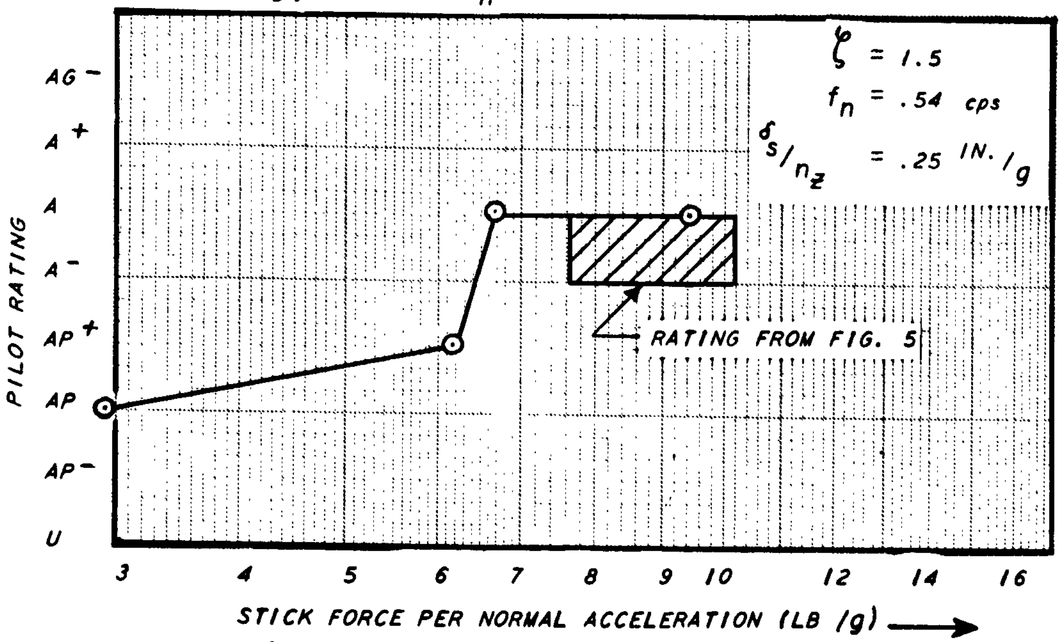


b.) LOW ζ LOW ω_n

Figure 10 STICK FORCE EVALUATION AT OTHER SHORT PERIOD DYNAMICS



c.) HIGH ζ, MODERATE ω_n



d.) HIGH ζ, MODERATE ω_n

Figure 10 (cont'd) STICK FORCE EVALUATION AT OTHER SHORT PERIOD DYNAMICS

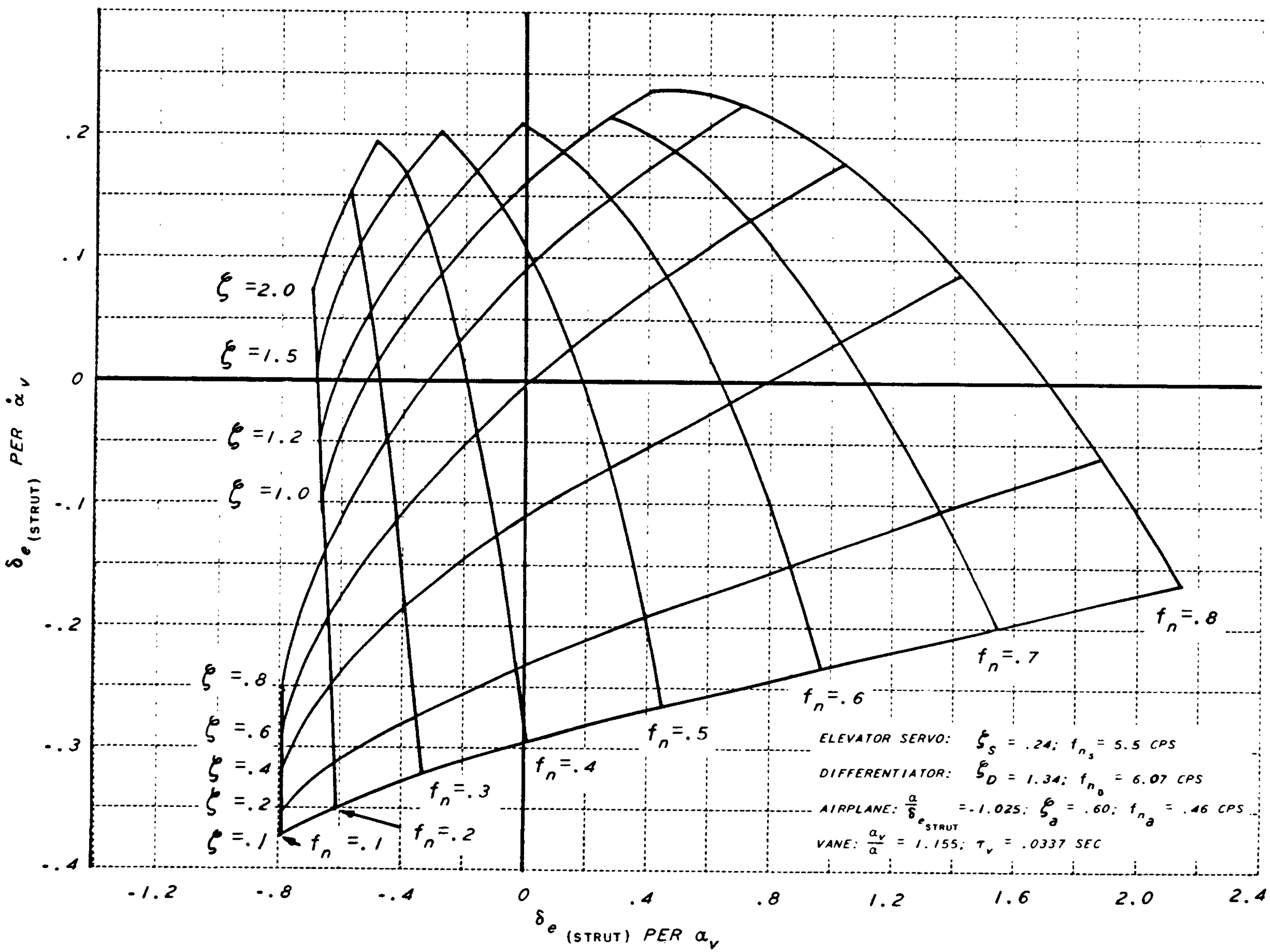


Figure 11 THEORETICAL PLOT OF SHORT PERIOD DAMPING RATIO AND NATURAL FREQUENCY VS ELEVATOR SERVO ARTIFICIAL STABILITY GAINS

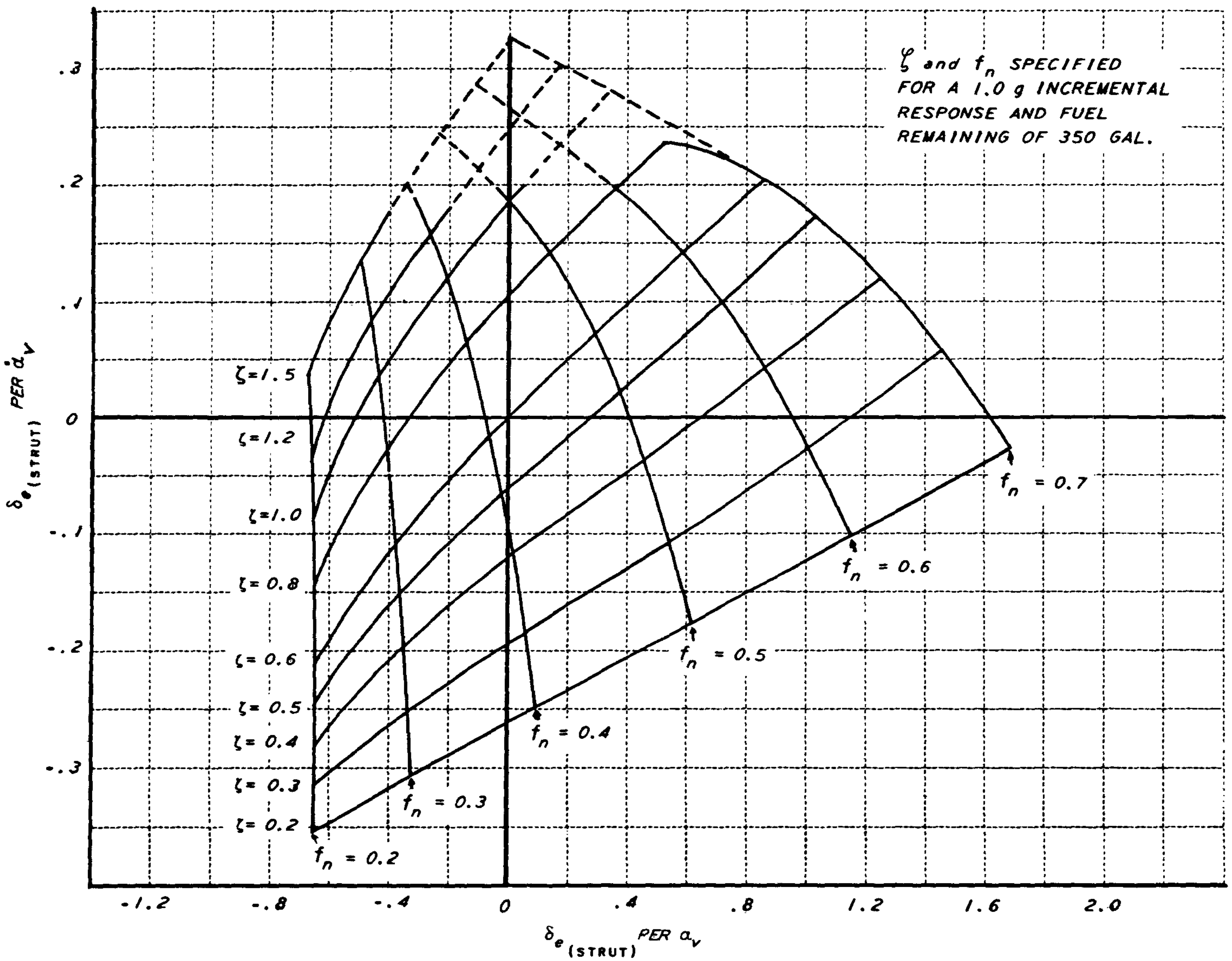


Figure 12 LEAST SQUARES FIT OF EXPERIMENTAL VALUES OF ζ AND f_n ON THEORETICAL GRIDWORK